

Direct-Photon Production from SPS to RHIC Energies

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Why Direct Photons? (I)

■ Direct Photons

- ◆ Pragmatic Definition:
Photons not coming from
hadron decays
- ◆ Difficult measurement:
Large Background from
 - $\pi^0 \rightarrow \gamma + \gamma$
 - $\eta \rightarrow \gamma + \gamma$

■ p+p:

- ◆ Late 1970's:
Direct Photons suggested
presence of pointlike
charged objects within
hadrons
- ◆ Test of QCD
- ◆ Focus now on constraining
gluon distribution functions
 - Quark-Gluon Compton
scattering contributes at
leading order (LO)
 - This is in contrast to Deep
Inelastic Scattering and Drell-
Yan where gluon is involved
only at NLO

Why Direct Photons? (II)

■ Nucleus+Nucleus collisions

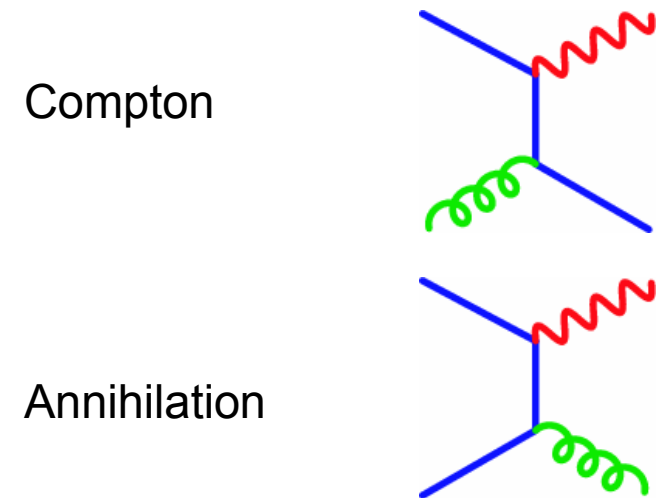
- ◆ Photons don't interact with the fireball and carry information about early stage of the A+A collision
- ◆ QGP potentially detectable via **thermal photon radiation**
- ◆ Thermal photons dominantly from early hot QGP phase:
→ **initial temperature**
- ◆ Direct Photons at high p_T
 - Allow test of N_{coll} scaling for hard processes
 - Important for interpretation of high p_T hadron suppression at RHIC

Direct Photon Production in p+p: Hard Scattering

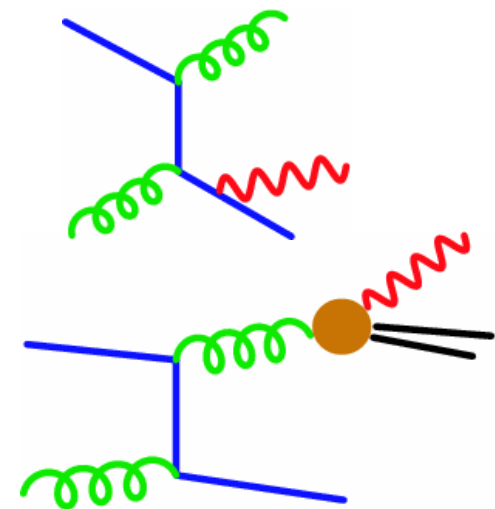
■ Processes in perturbative QCD

- ◆ Compton: $q + g \rightarrow \gamma + q$
 - ◆ Annihilation: $q + \bar{q} \rightarrow \gamma + g$
 - ◆ Bremsstrahlung
- LO } NLO

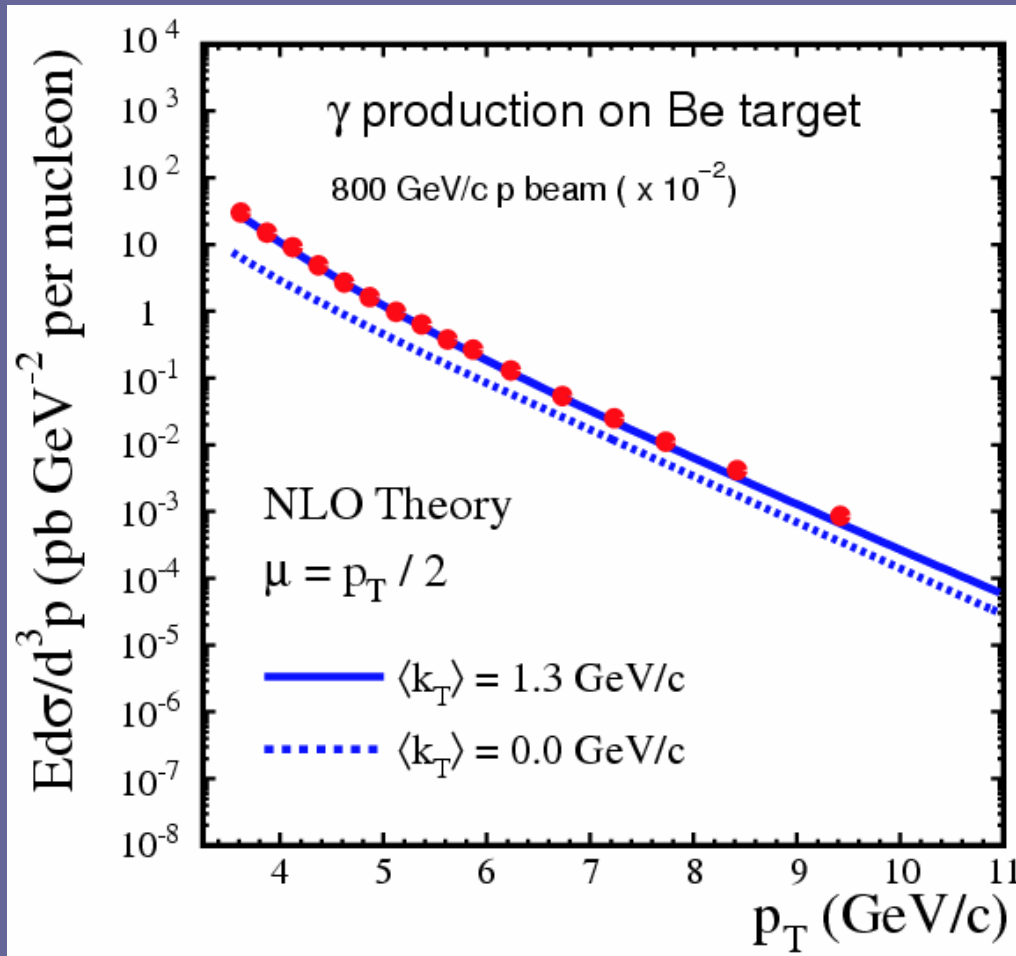
- Typically 20-30% uncertainty in pQCD calculations related to choice of scales



Bremsstrahlung

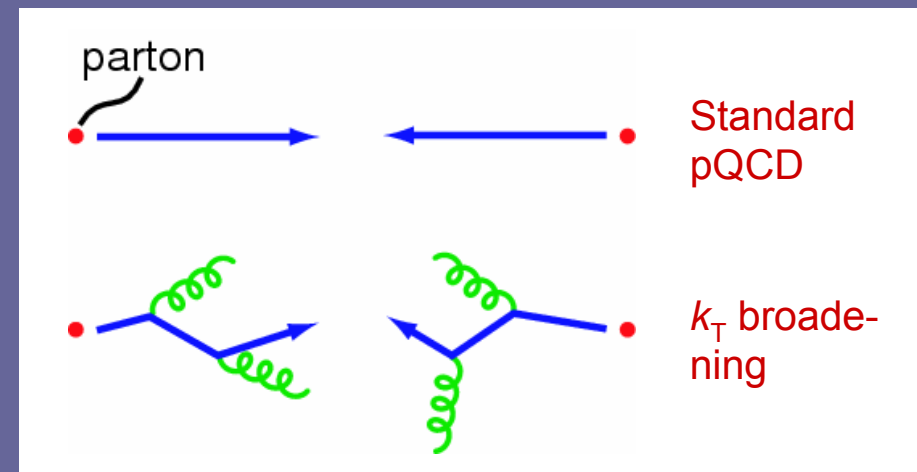


Evidence for k_T Broadening

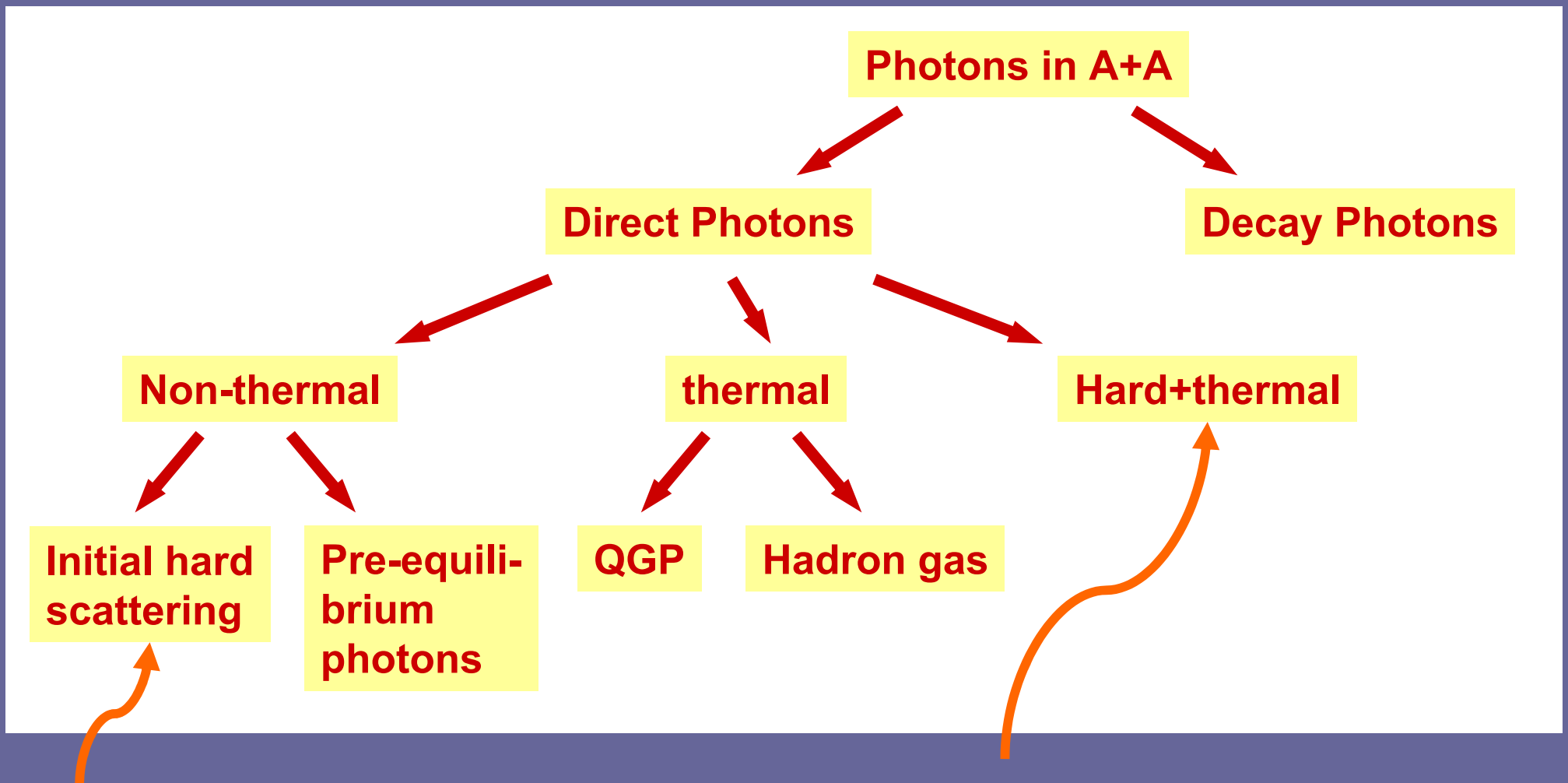


E706, hep-ex/0407011

- Systematic pattern of deviation between NLO pQCD and data
 - ◆ Data above pQCD
 - ◆ Especially at low \sqrt{s}
- Possible explanation:
 k_T broadening (which can be produced by multiple soft-gluon emission)



Photon Sources in A+A



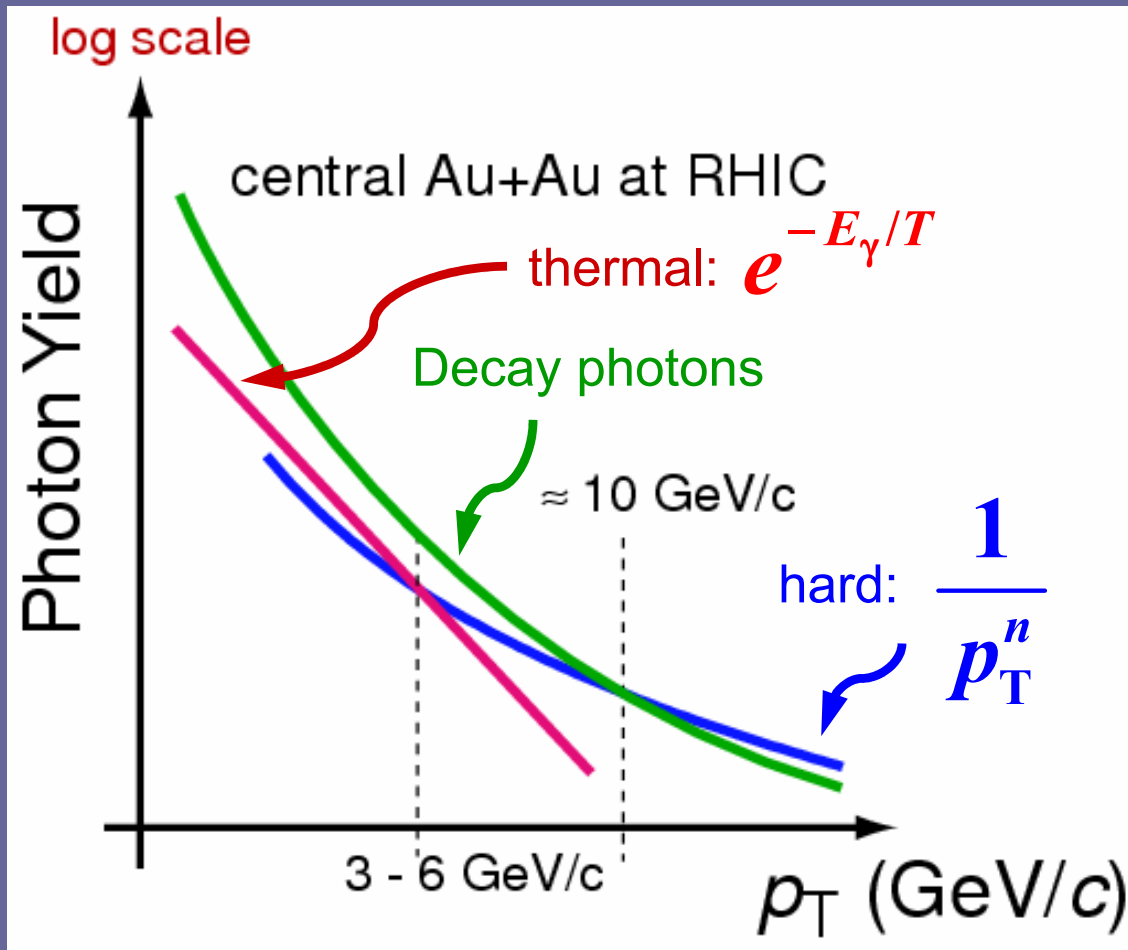
pQCD or
prompt photons

Interaction of hard parton with QGP

1) $q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g$ and $q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q$

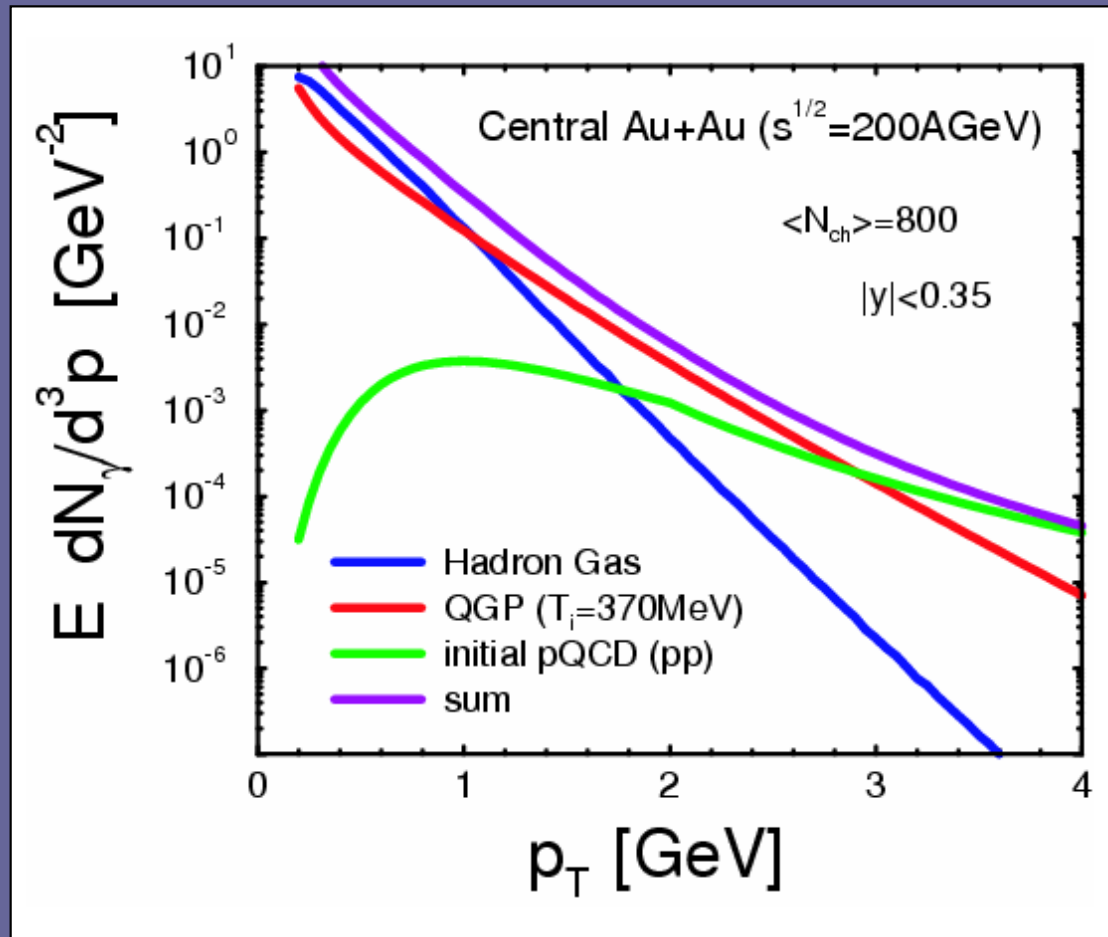
2) Medium induced photon bremsstrahlung

Schematic Photon Spectrum in A+A



- Advantage in central A+A at RHIC:
Decay photon background strongly reduced due to π^0 suppression

Realistic Calculation



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

- Window for thermal photons from QGP in this calculation:
 $p_T = 1 - 3 \text{ GeV}/c$

Thermal Photons as QGP Signature

■ Conventional wisdom ca 1985:

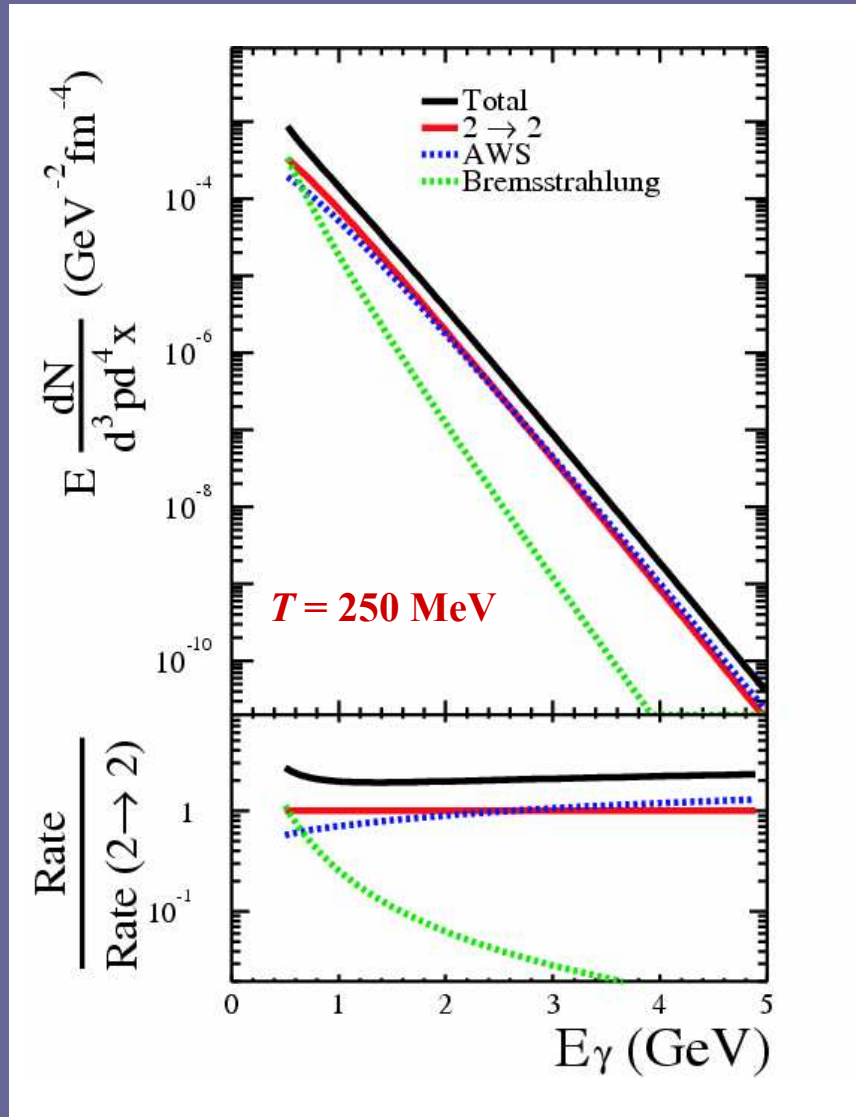
- ◆ QGP has lots of quarks flying around
- ◆ QGP radiates more than HG at the same temperature (**false!**)
- ◆ Lots of thermal radiation is evidence for QGP

■ Current conventional wisdom:

- ◆ QGP has more d.o.f. than HG and therefore lower temperature at the same energy density ϵ ($\epsilon \sim g \cdot T^4$)
- ◆ At the same energy density QGP radiates less than HG
- ◆ Lack of radiation is evidence for QGP!

See talk by P. Stankus at CTEQ
summer school 2004: <http://www.cteq.org>

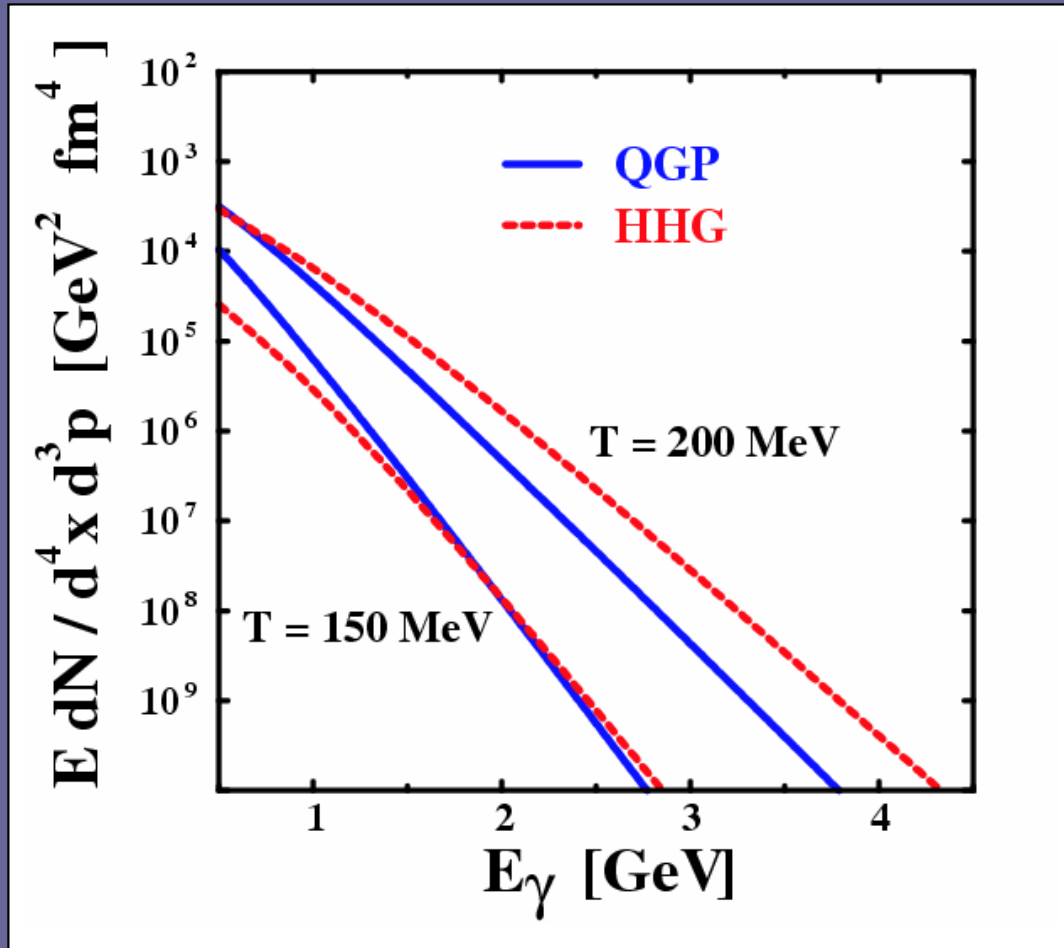
Thermal Photon Rates in QGP



State-of-the-art result from Arnold, Moore, and Yaffe (including Landau-Pomeranchuk-Migdal destructive interference effect)

- Final thermal photon spectrum: QGP and HG photon rates convoluted with space-time evolution of the reaction
- Thermal photon rate in QGP
 - ◆ Hard-thermal-loop resummation
 - ◆ Effective in-medium Quark and Gluon propagators
 - ◆ Processes
 - $2 \rightarrow 2$ {
 - Quark-Gluon-Compton scattering
 - Quark-antiquark annihilation
 - Annihilation with Scattering (AWS)
 - Bremsstrahlung

Photon Rates in HG and QGP



- Typical processes for direct photon production in hot hadron gas (HHG)



- Hadron gas at $T=200 \text{ MeV}$ radiates more than QGP at the same temperature

Steffen and Thoma, Phys. Lett. B 510, 98 (2001)

Measurement of Direct Photons

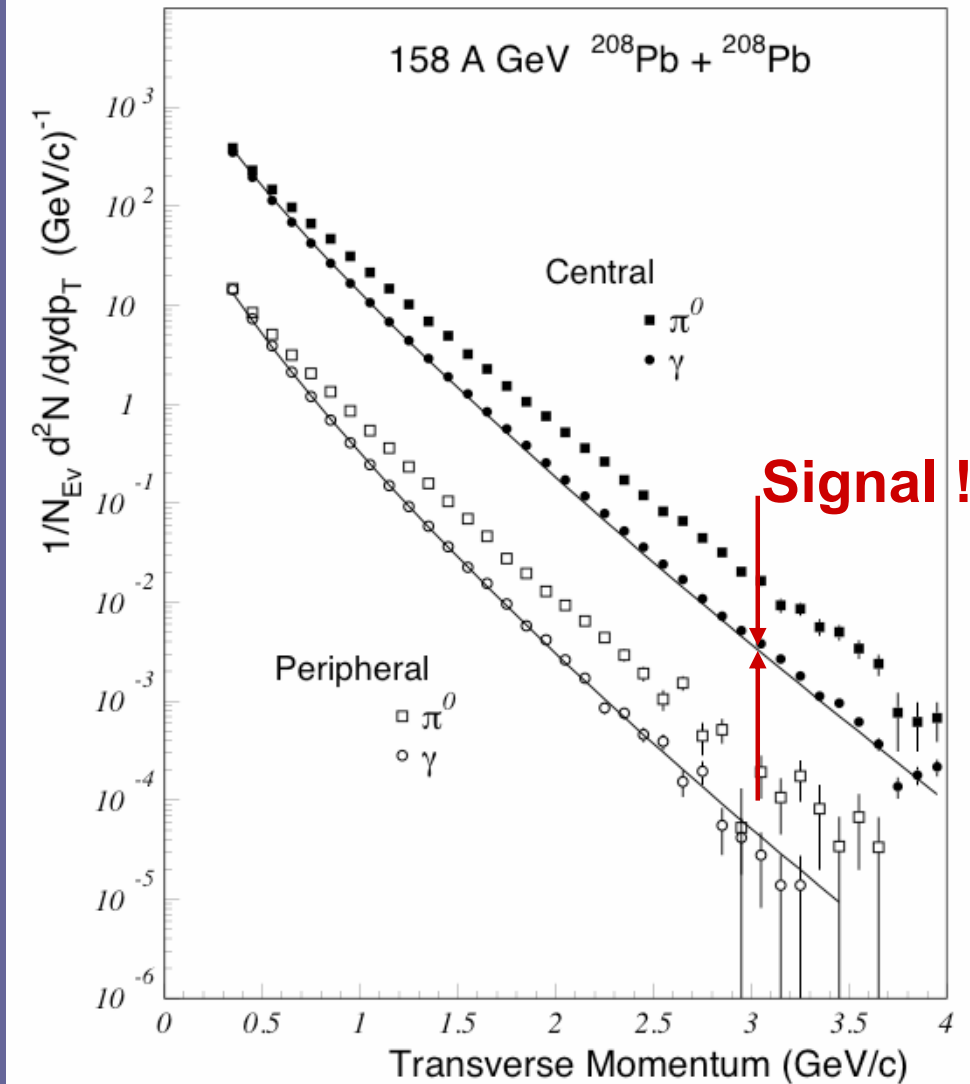
- Measure p_T spectrum of π^0 and η mesons with high accuracy
- Calculate number of decay photon per π^0
 - ◆ Usually with Monte-Carlo
 - ◆ m_T scaling for (η) , η' , ω , ...
- Get clean inclusive photon sample
 - ◆ Charged background subtraction
- Finally:
Subtract decay background from inclusive photon spectrum

Handy formula:

$$\frac{d\sigma}{dp_T} \propto 1/p_T^n$$
$$\Rightarrow \frac{\gamma_{\pi^0}^{\text{decay}}}{\pi^0} = \frac{2}{n-1} \approx 0.28 \text{ at RHIC}$$

$$"\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}"$$

Why this is Difficult

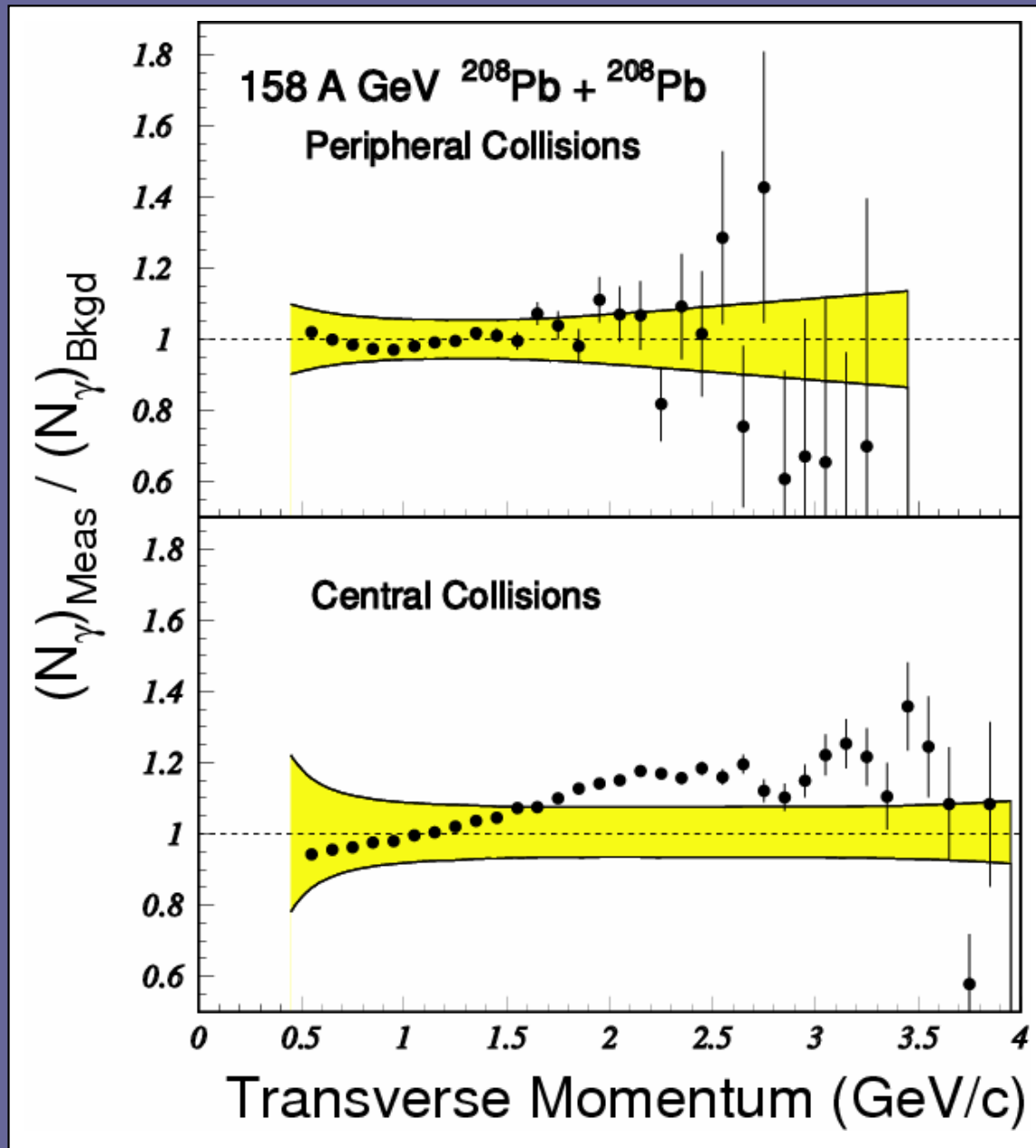


Systematic errors
(e.g. energy scale non-linearity)
partially cancel in this ratio

$$R = \frac{\gamma_{\text{measured}}}{\gamma_{\text{decay}}} = \frac{(\gamma / \pi^0)_{\text{measured}}}{(\gamma / \pi^0)_{\text{decay}}}$$

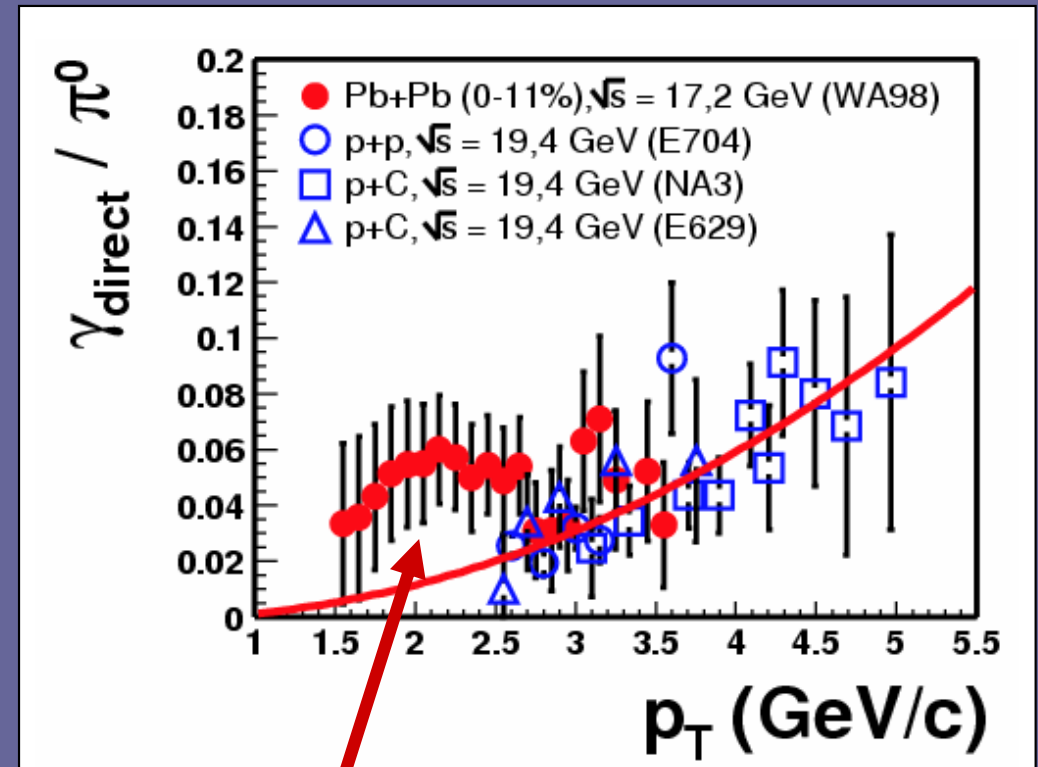
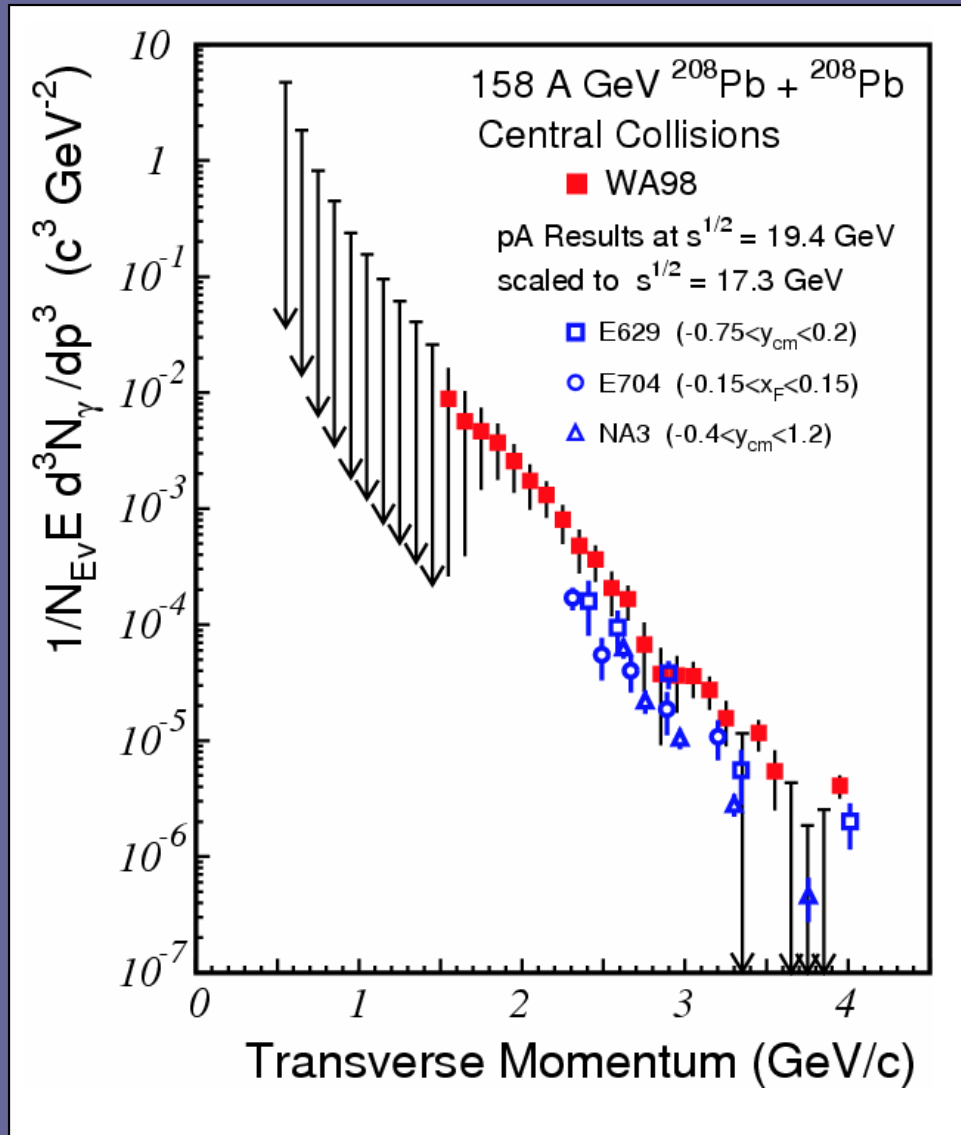
$$\gamma_{\text{direct}} = \left(1 - \frac{1}{R}\right) \cdot \gamma_{\text{measured}}$$

WA98 Result

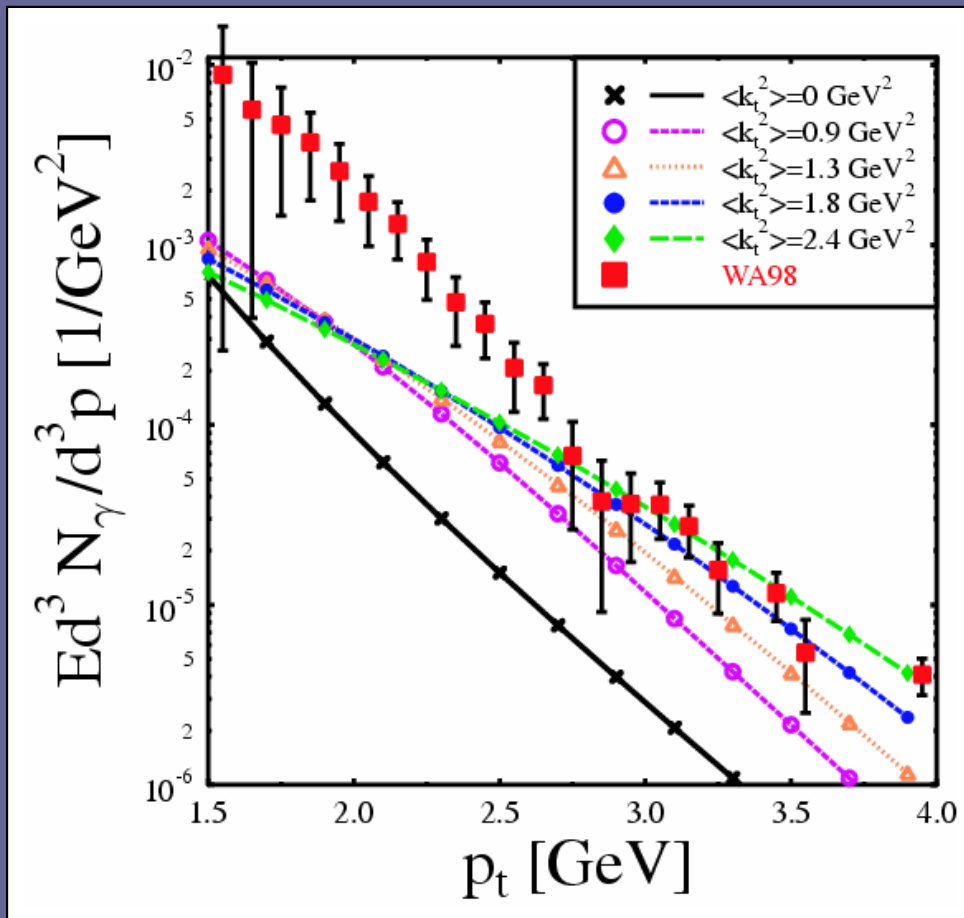


- 20% direct photon excess at high p_T in central Pb+Pb collisions at CERN SPS
- No signal within errors in peripheral collisions

WA98 Direct Photon Spectrum



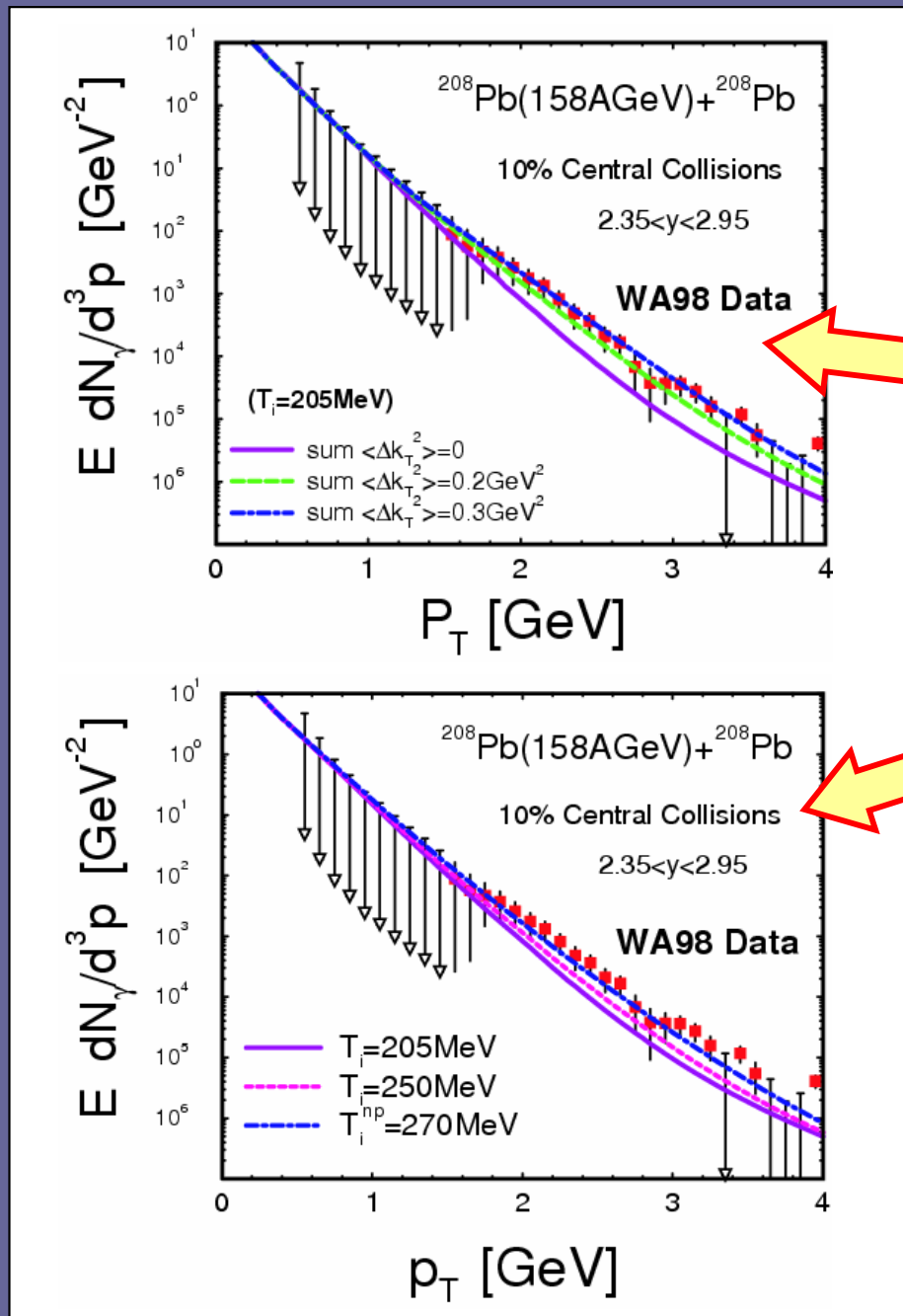
WA98 Interpretation I: pQCD with Nuclear k_T Broadening ?



Dumitru et al., Phys. Rev. C 64, 054909 (2001)

- High p_T part of the spectrum explained by pQCD + nuclear k_T broadening
 - ◆ p+p: $\langle k_T^2 \rangle \approx 1.4 \text{ GeV}^2$
 - ◆ A+A: $\langle k_T^2 \rangle \approx 2.4 \text{ GeV}^2$
- Intermediate p_T range cannot be explained regardless of amount of k_T

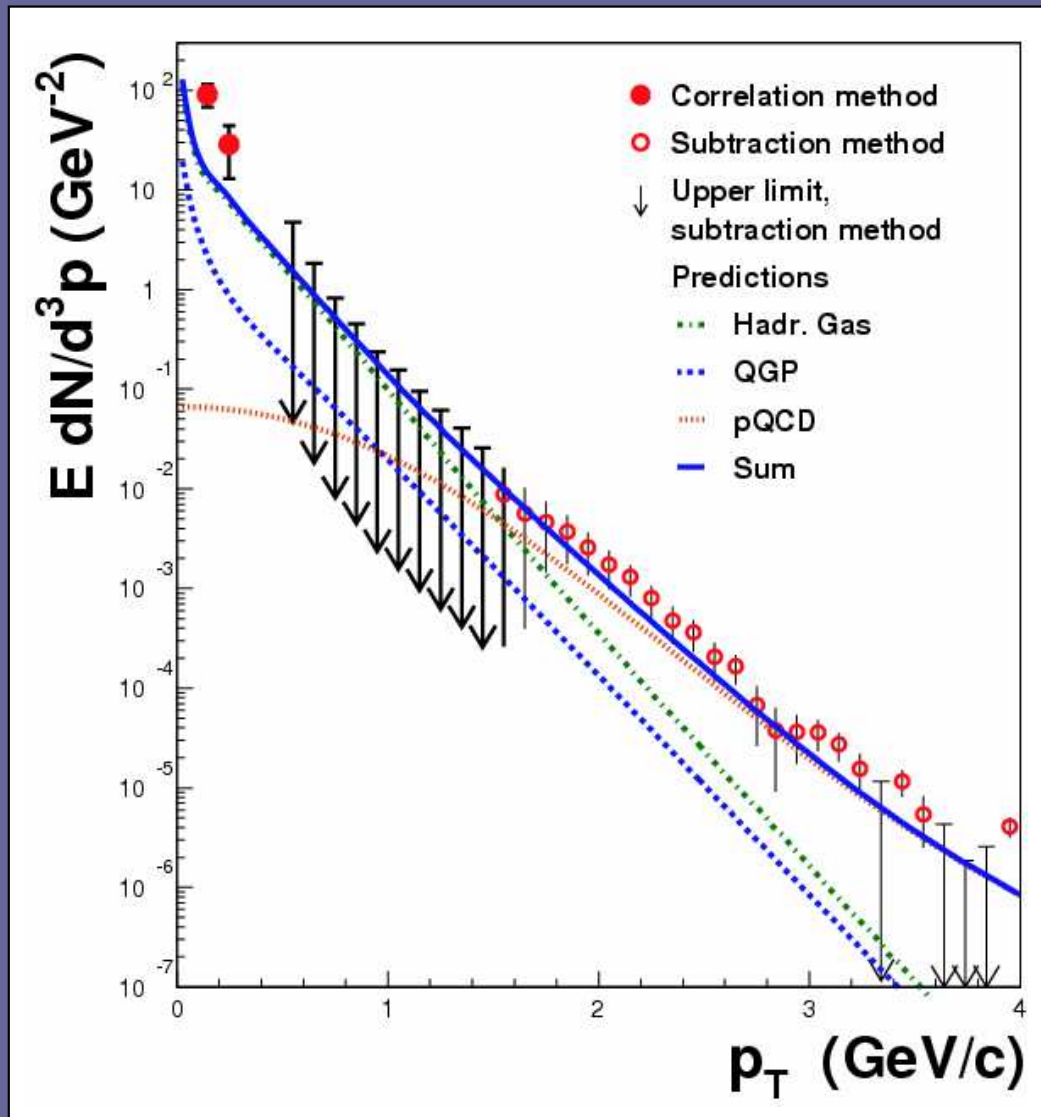
WA98 Interpretation II: T or k_T ?



- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature $T_i=205 \text{ MeV}$ + some nuclear k_T broadening (Cronin-effect)
- Data also described without k_T broadening but with high initial temperature ($T_i=270 \text{ MeV}$)
- Other Models (see e.g. Huovinen et al., Nucl. Phys. A 650 (227) 1999) explain data without assuming QGP

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014902), 2004

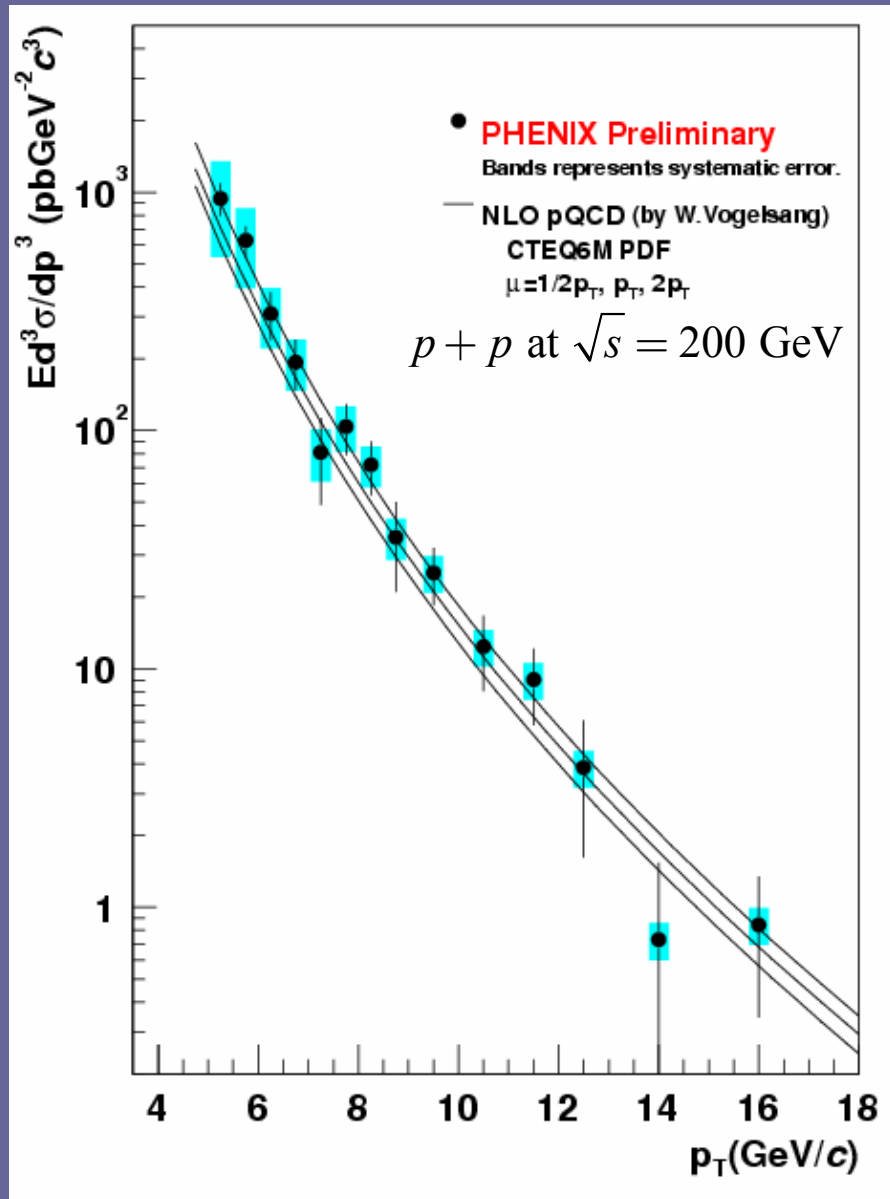
WA98: New low- p_T Points



- Two photon correlations observed and attributed to Bose-Einstein correlations of direct photons
- Correlation strength used to extract direct photon signal at low p_T
- New points not described by current models

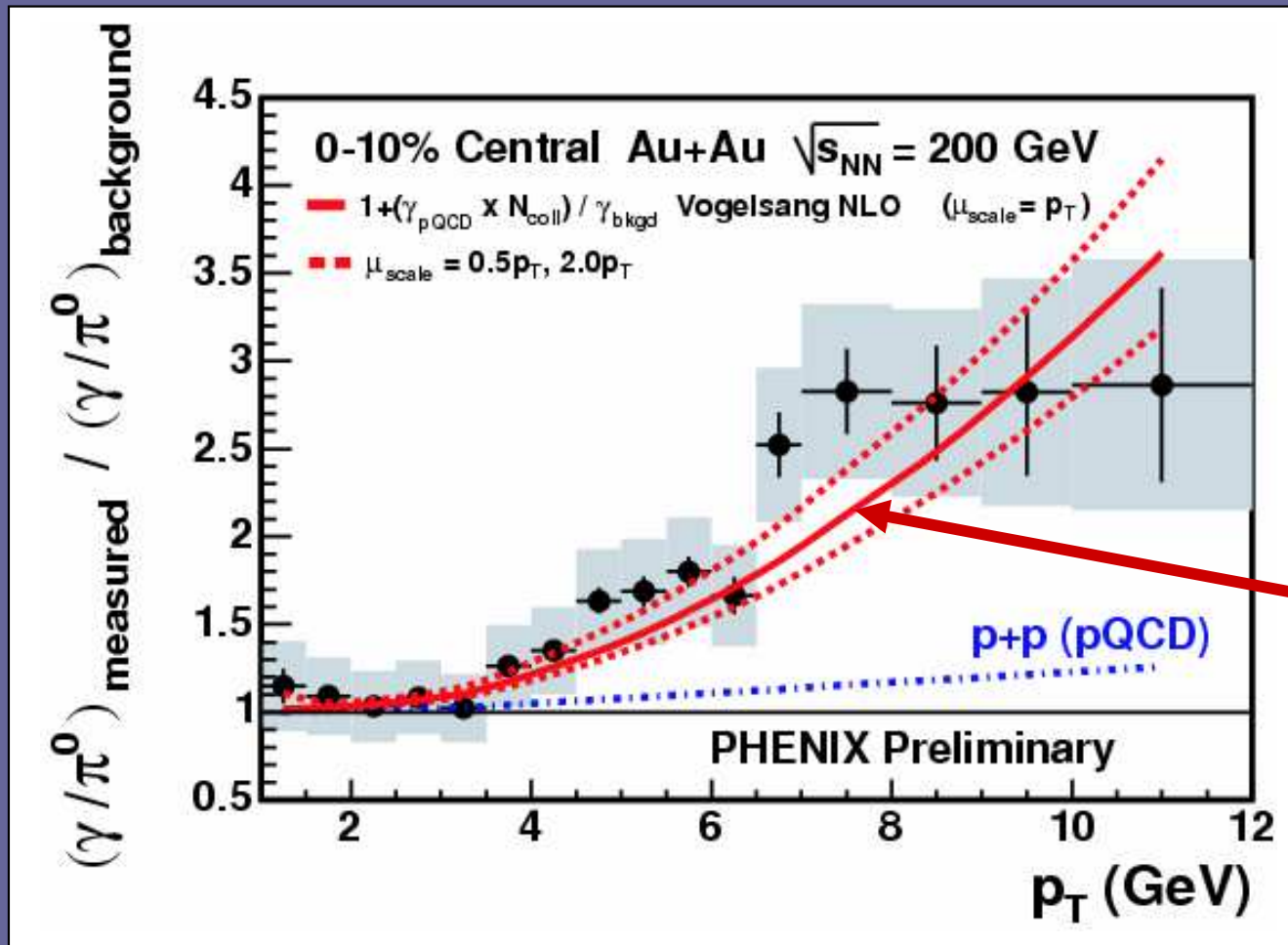
WA98, Phys. Rev. Lett. 93 (022301), 2004

Direct Photons at RHIC: p+p



- Data show good agreement with NLO pQCD calculation
- Important baseline for interpretation of Au+Au results

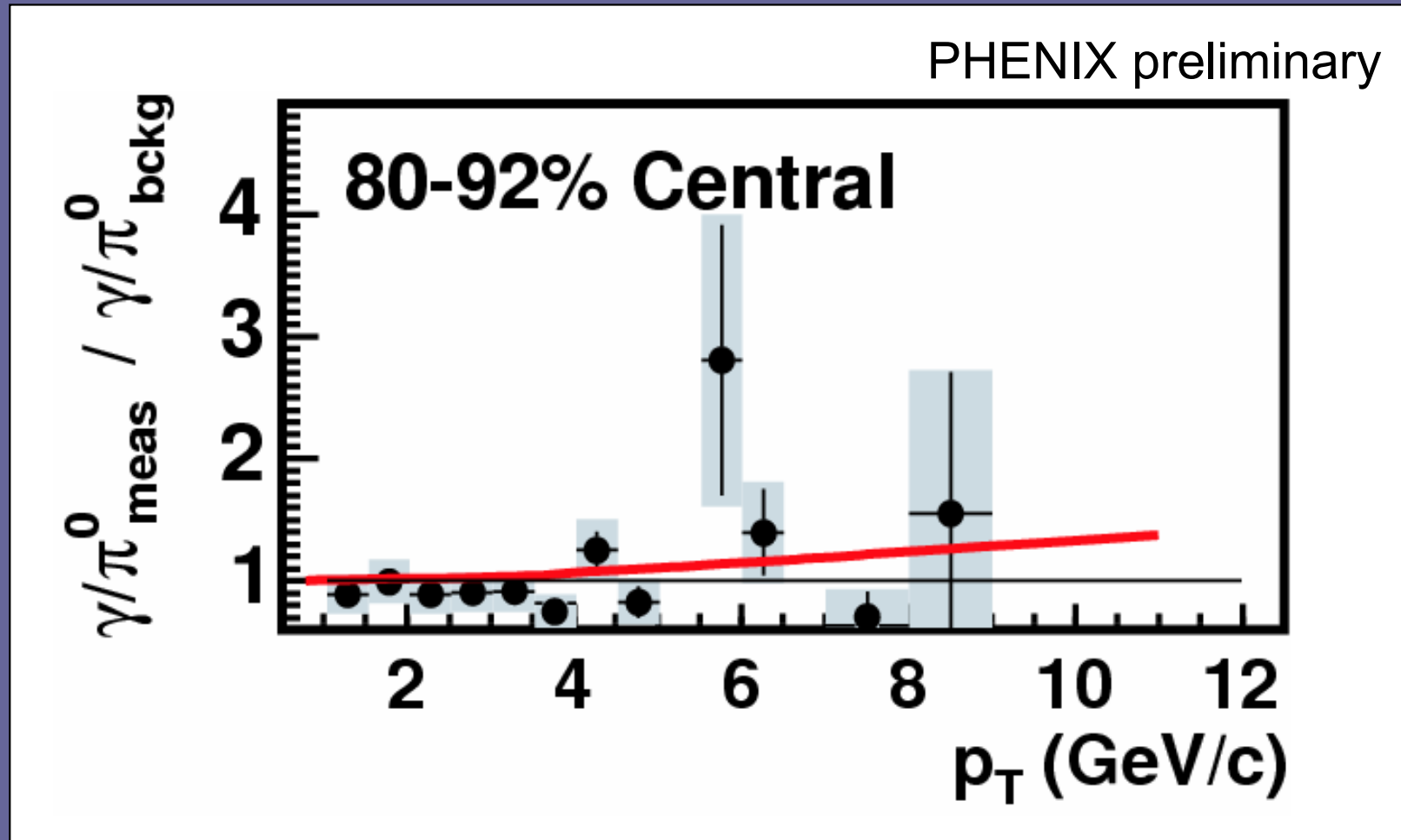
Direct Photons at RHIC: Au+Au



Expectation for N_{coll} scaling of direct photons

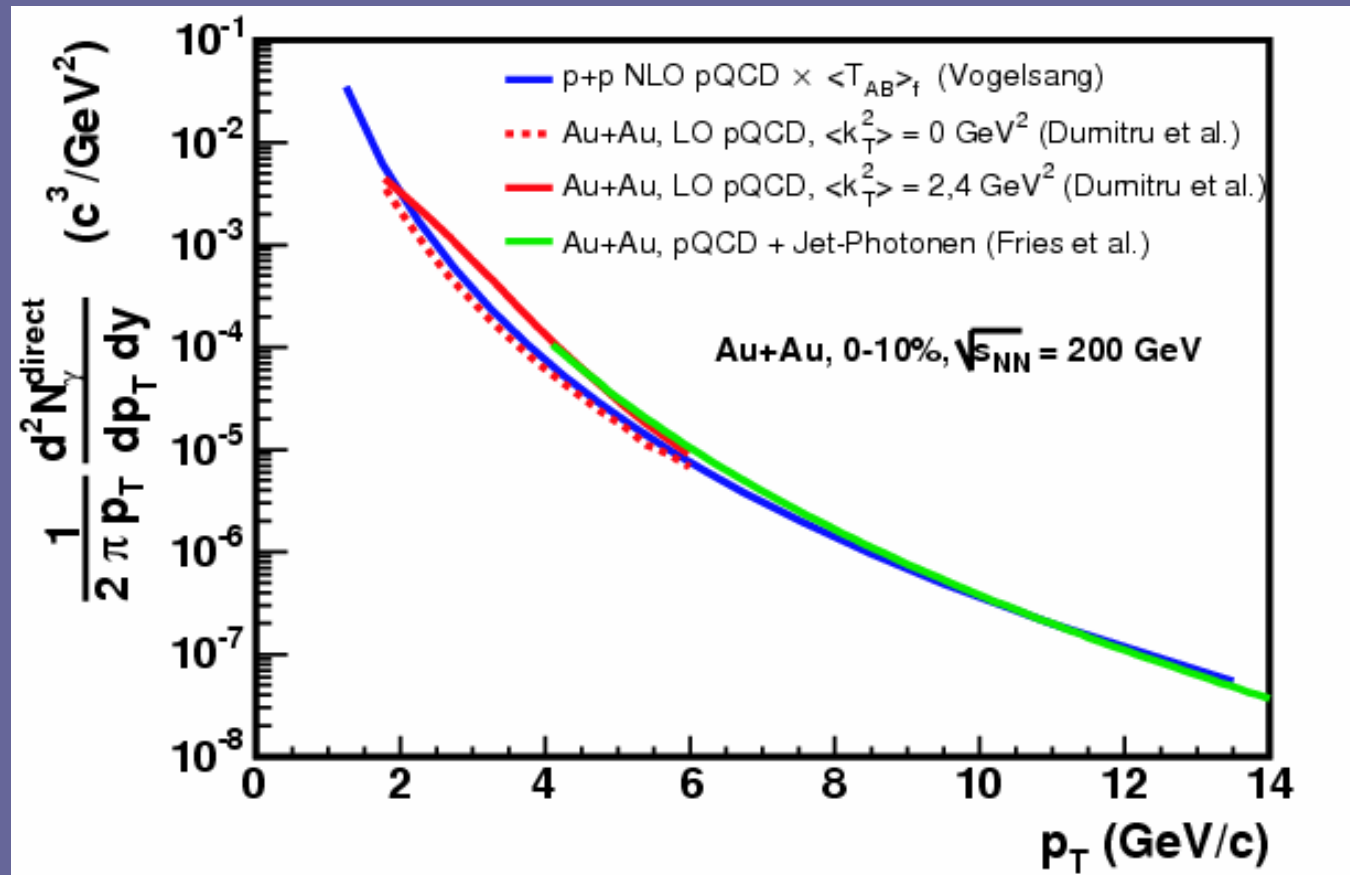
- Strong direct photon signal in central Au+Au
- Direct Photons at high p_T follow N_{coll} scaling
- Errors currently too large for statement about thermal photon signal

Centrality Dependence



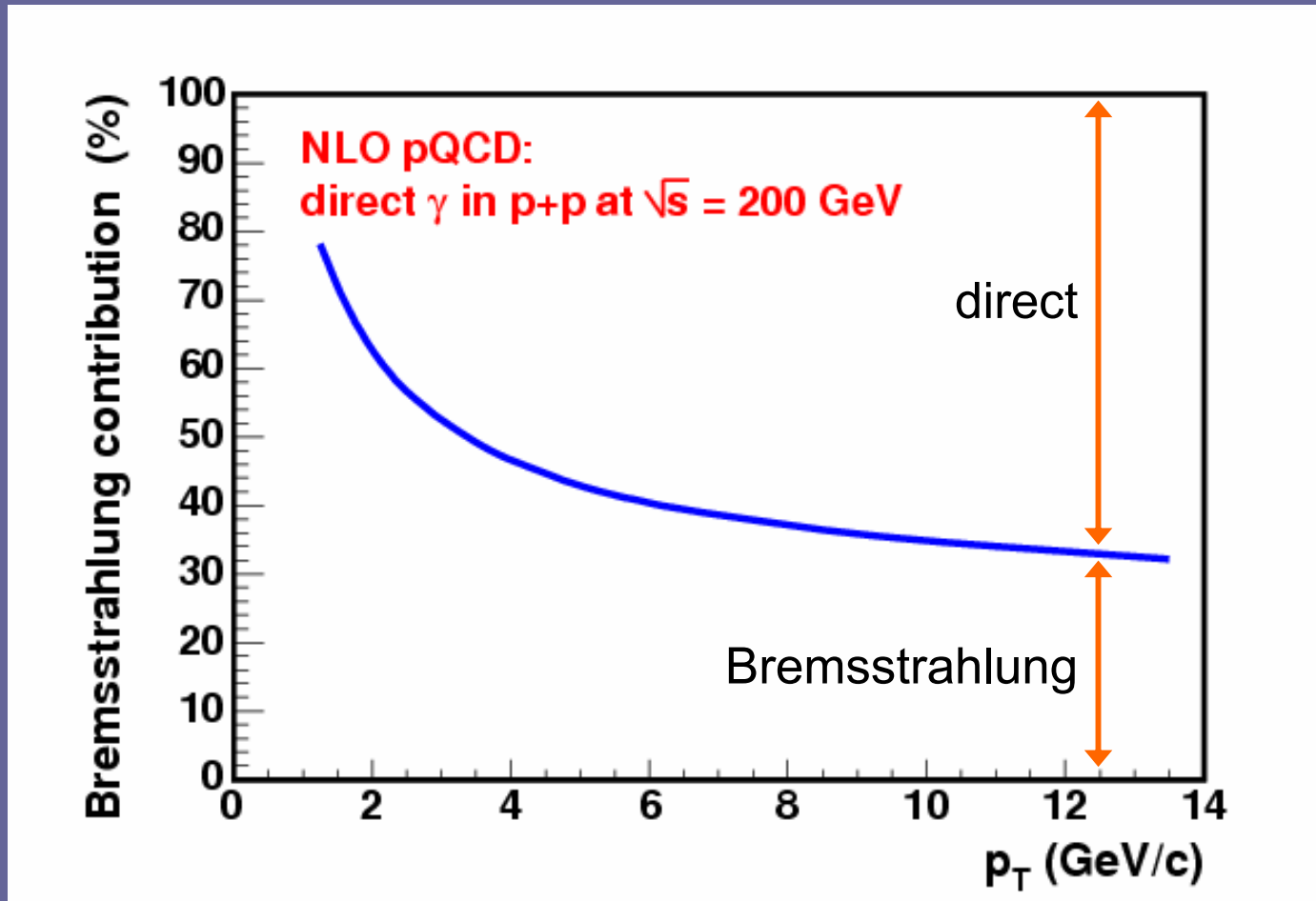
- N_{coll} scaling holds for all centrality classes (within errors)

Beyond simple N_{coll} Scaling: k_T Effects and Photons from Quark-Jets



- Effect of k_T strongest where thermal QGP photons are expected
- Interaction of fast quarks with QGP significant photons source for $p_T < 6 \text{ GeV}/c$ (Jet-Photons: $q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g$ and $q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q$)

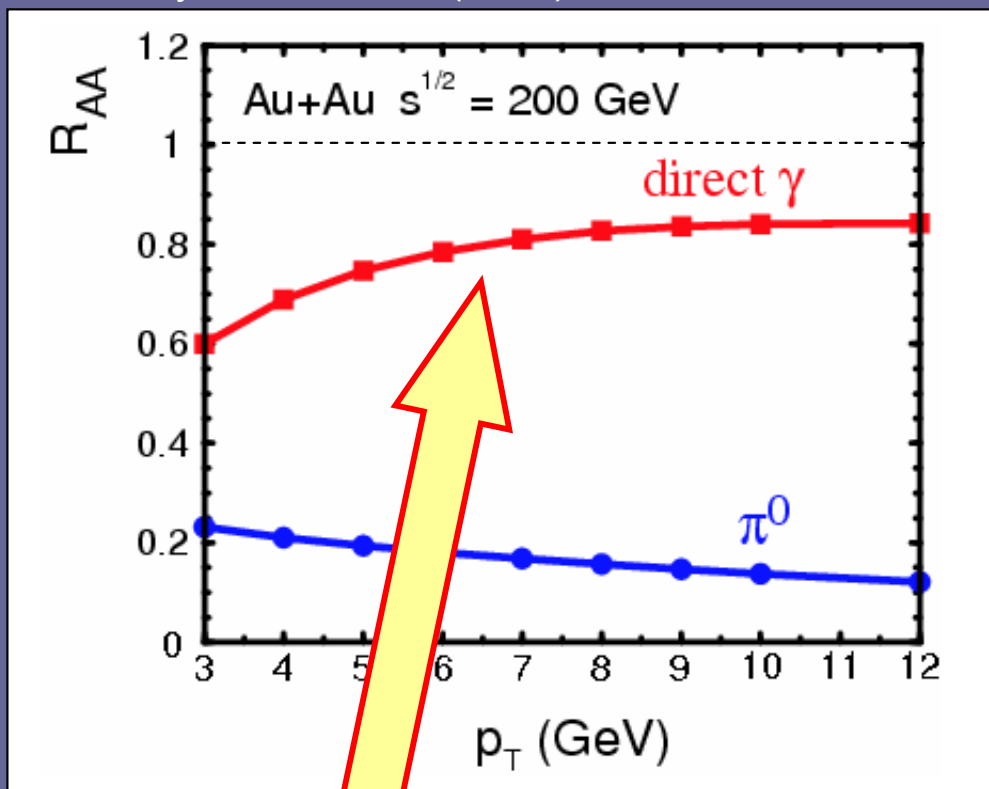
What about Photon Bremsstrahlung in A+A ?



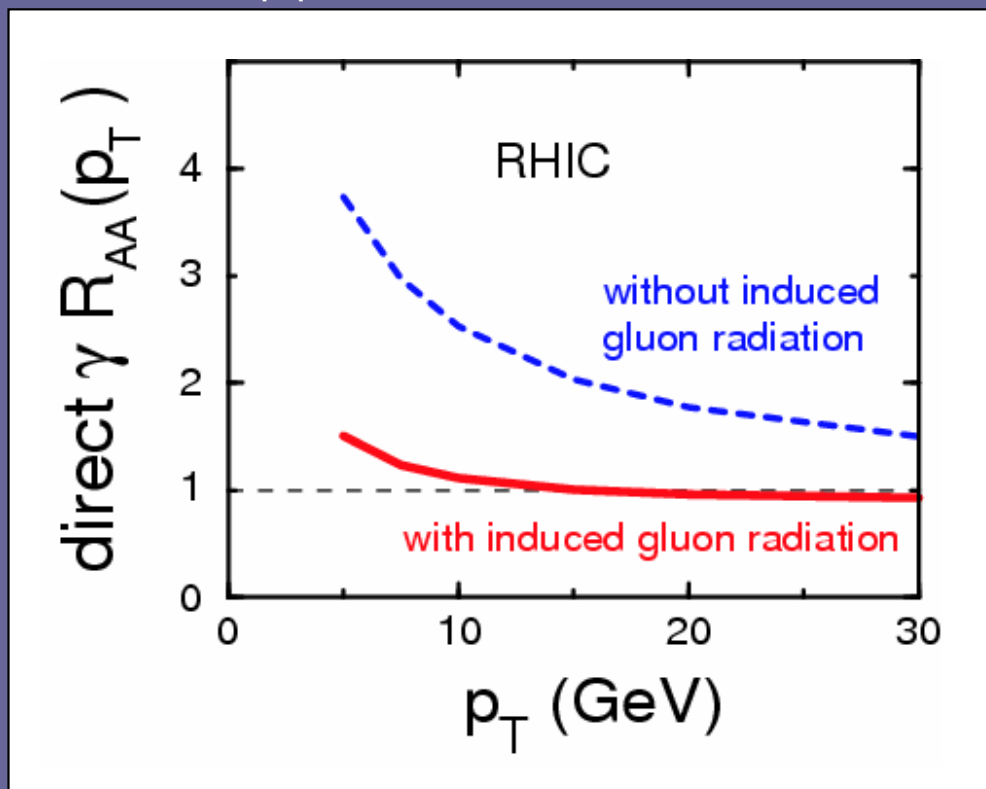
- Bremsstrahlung contribution large
- Modification of Bremsstrahlung contribution expected in A+A

Modification of Bremsstrahlung Contribution in A+A

Jeon, Jalilian-Marian, Sarcevic,
Nucl. Phys. A 715, 795 (2003)



Zakharov, hep-ph/0405101



- Quark energy loss in QGP reduces bremsstrahlung contribution in A+A
- However, this is compensated by induced photon bremsstrahlung in QGP (according to Zakharov)
- Net result: direct photon $R_{AA} \geq 1$ at high p_T

Model-independent Representation of π^0 Suppression

- Standard representation relies on assumptions about scaling of hard scattering processes in A+A:

$$R_{AA} = \frac{d^2 N / dp_T dy|_{A+A}}{\langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}^{\text{pp}} \times d^2 \sigma / dp_T dy|_{p+p}}$$

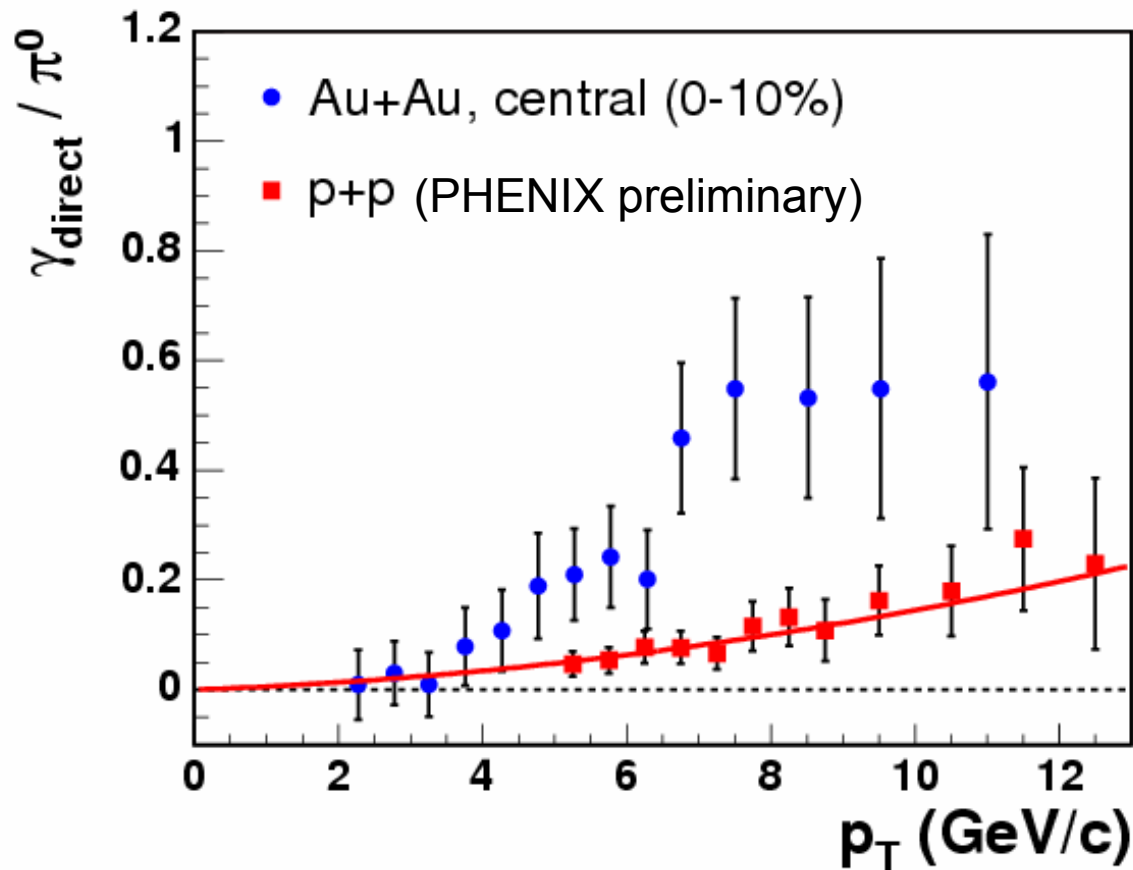
- PHENIX result on high p_T direct photon production confirms this assumption
- However, it seems natural to avoid model assumptions and to use high p_T direct photons as a direct measure of the number of hard scatterings in A+A

- Define:

$$G_{AA} = \frac{(\gamma_{\text{direct}} / \pi^0)_{p+p}}{(\gamma_{\text{direct}} / \pi^0)_{A+A}}$$

- If direct photons exactly follow N_{coll} scaling then
 $G_{AA} = R_{AA}$

$\gamma_{\text{direct}} / \pi^0$

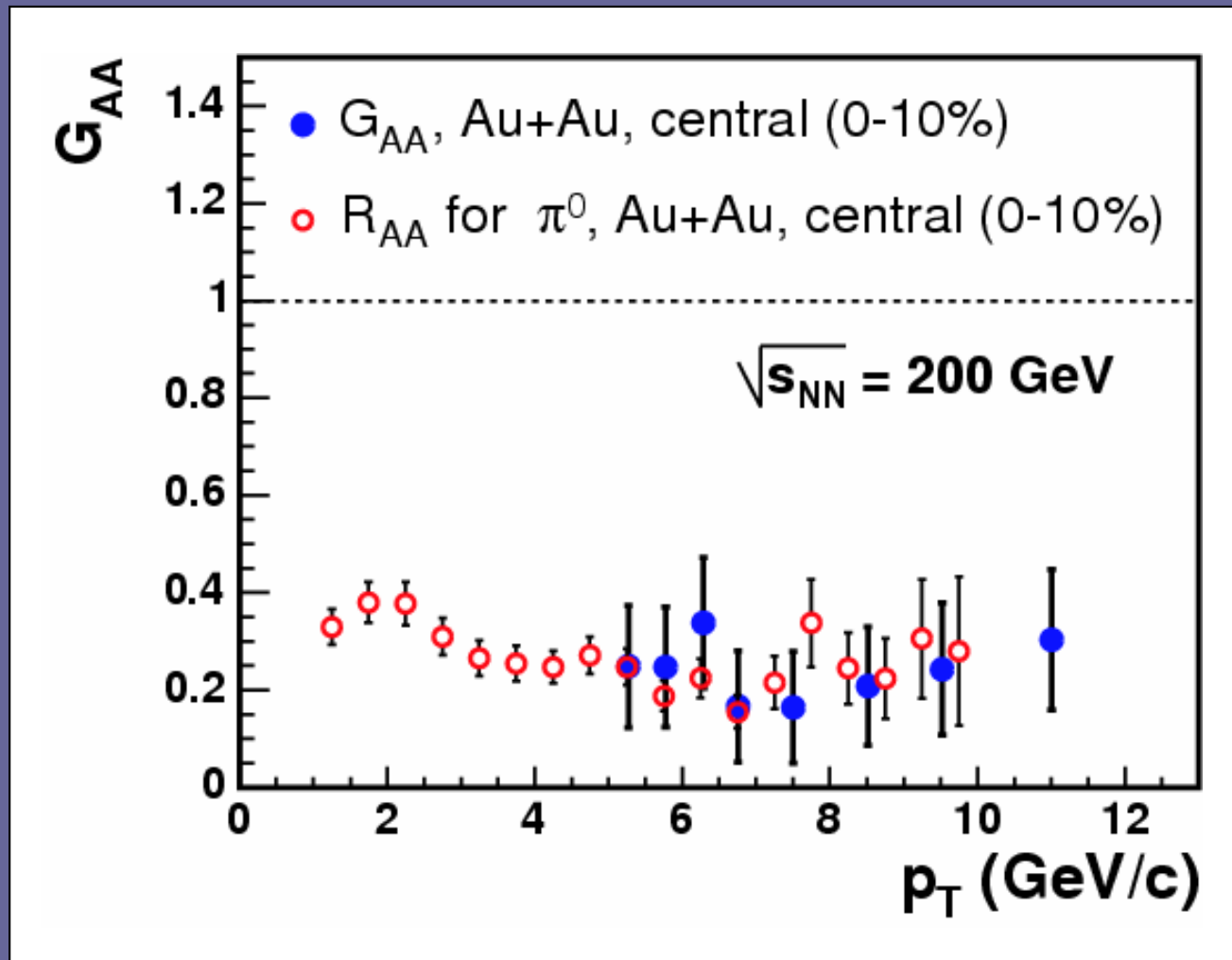


Blue points are another representation of the PHENIX preliminary double ratio:

$$\left(\frac{(\gamma / \pi^0)_{\text{measured}}}{(\gamma / \pi^0)_{\text{decay}}} - 1 \right) \times 0.3$$

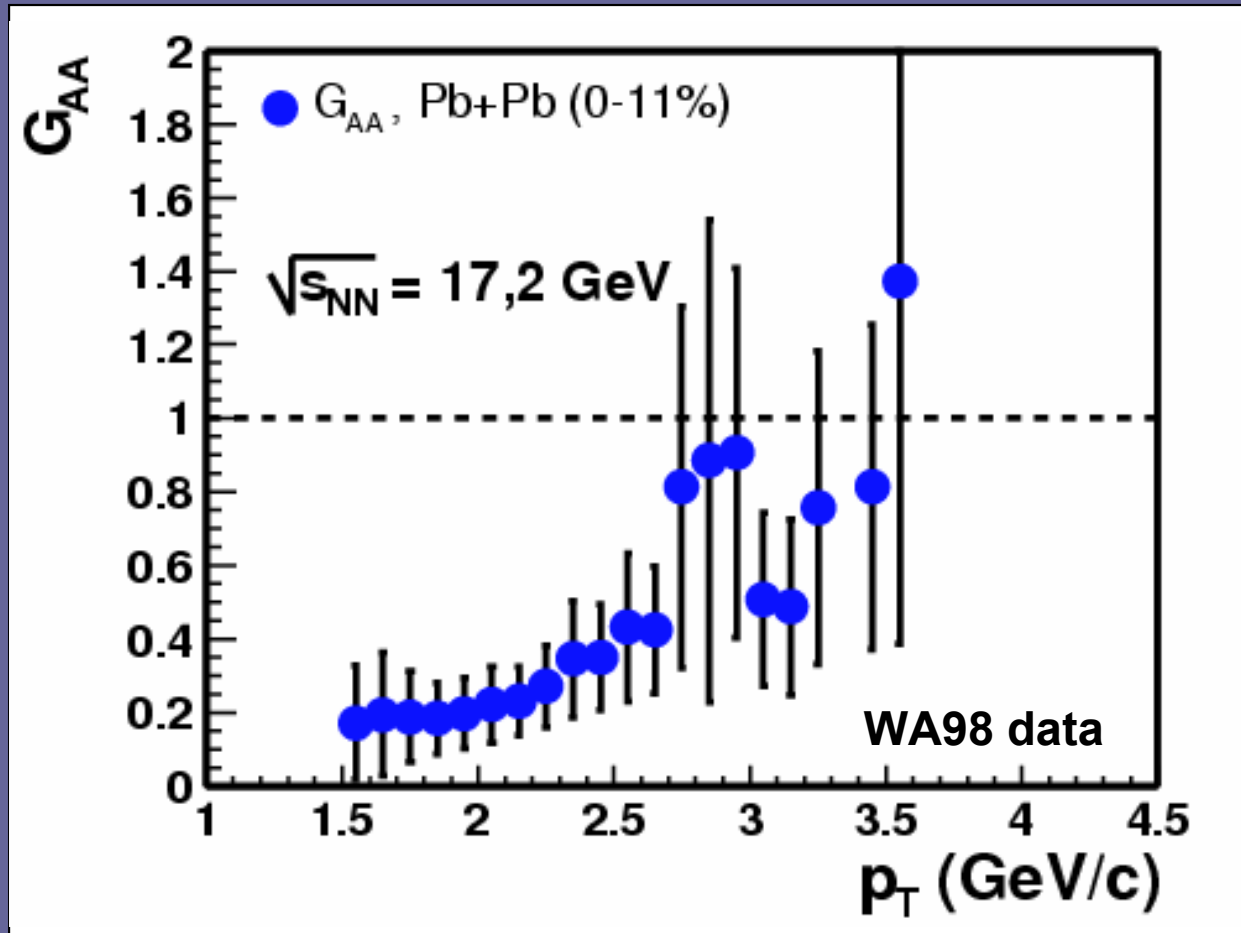
$(\gamma/\pi^0)_{\text{decay}}$
above $p_T = 3 \text{ GeV}/c$

G_{AA} in central Au+Au at RHIC



- G_{AA} agrees well with the standard R_{AA} representation of the neutral pion suppression

G_{AA} at CERN SPS



- G_{AA} consistent with 1 at high p_T ($p_T > 3$ GeV/c)
- Moderate π^0 suppression also consistent with data

Summary

- Pb+Pb at CERN SPS:
Direct photon signal consistent with QGP scenario, however, models without QGP are also able to explain the data
- Au+Au at RHIC:
Direct photon signal observed at high p_T confirms N_{coll} scaling for hard processes and supports explanation of pion suppression as final state effect

Backup Slides

R_{AA} for Different Energies

